# Energy and sustainable development

Damien Ernst – University of Liège (email: dernst@uliege.be)

## Chapter 6 – Solar Energy

*Panda Green Energy Group's 100 MWc solar farm - Datong County, China.*

# Solar irradiance in Belgium

| |
|---|
| The power of raw sunshine at the equator at midday on a cloudless day: 1000 $W/m^2$ |

Corrections to be made to get power per square meter of land area in Belgium:

- Compensation between the tilt of the sun and the land;
- Not midday all of the time (32% of a day);
- In Belgium, the sun shines on average 35% of daylight hours.

The average power per $m^2$ of flat ground in Belgium ≈ **117 $W/m^2$**.

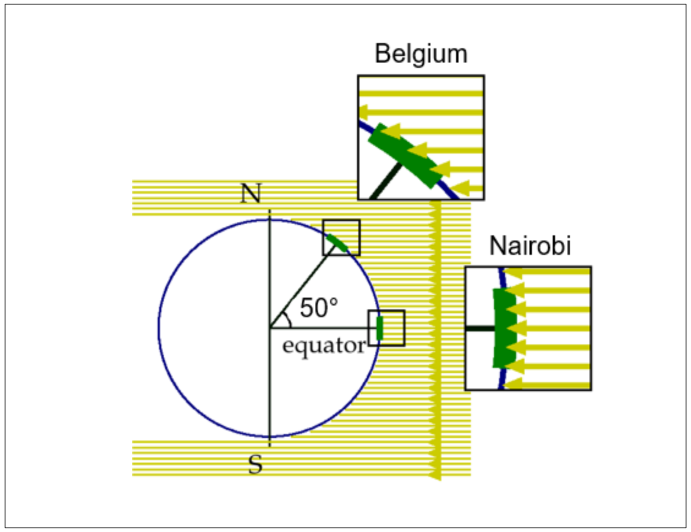


*Figure 1: Sunlight hitting the earth at midday on a spring day.*

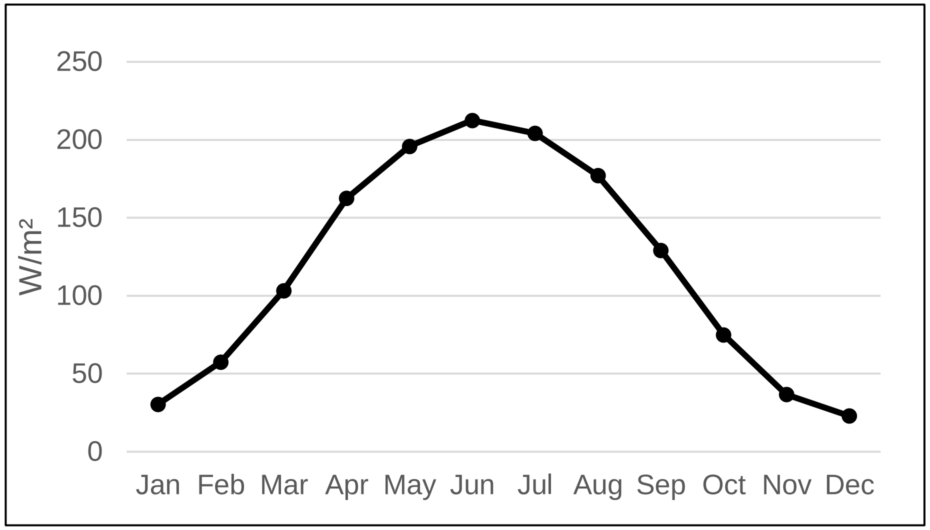


*Figure 2: Average monthly solar irradiance in Liège (1990 - 2020).*

# Solar irradiance in other countries

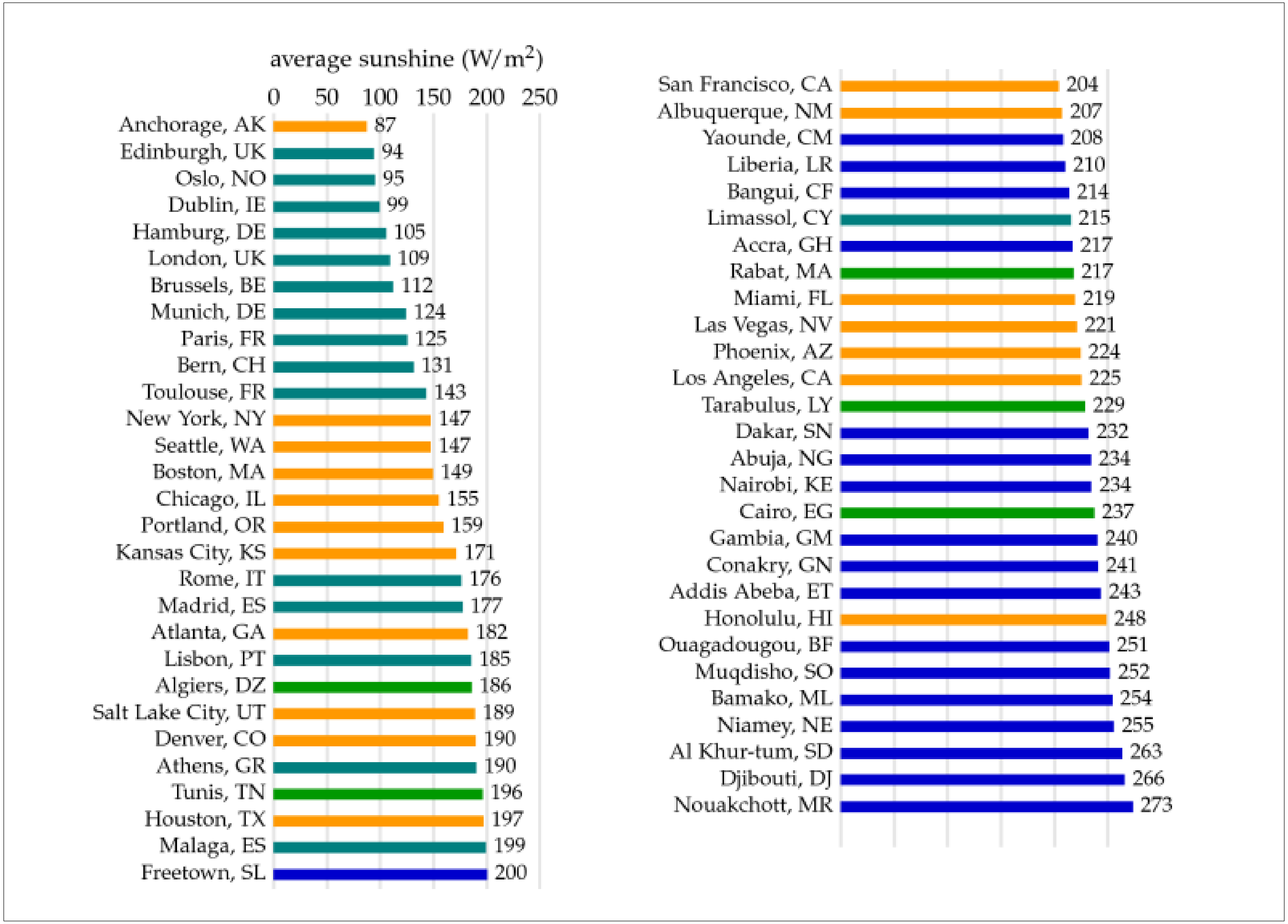


*Figure 3: Average solar irradiance in different cities of the world.*

# Turning raw solar power into useful power

1. **Solar photovoltaic**: generating electricity.

2. **Solar thermal**: using sunshine for direct heating of buildings or water.

3. **Solar biomass**: using trees, bacteria, algae, corn, etc. to make energy fuels, chemicals, or building materials.

4. **Food**: same as solar biomass except that the plants are used to feed humans or animals. (will be seen in another upcoming chapter).

# Solar photovoltaic – The photovoltaic effect

The photovoltaic effect is the ability to transform solar energy into electricity.
It depends on two physical quantities: irradiance and temperature.
An increase in irradiance increases the power generated by the solar panel while an increase of temperature causes it to decrease.

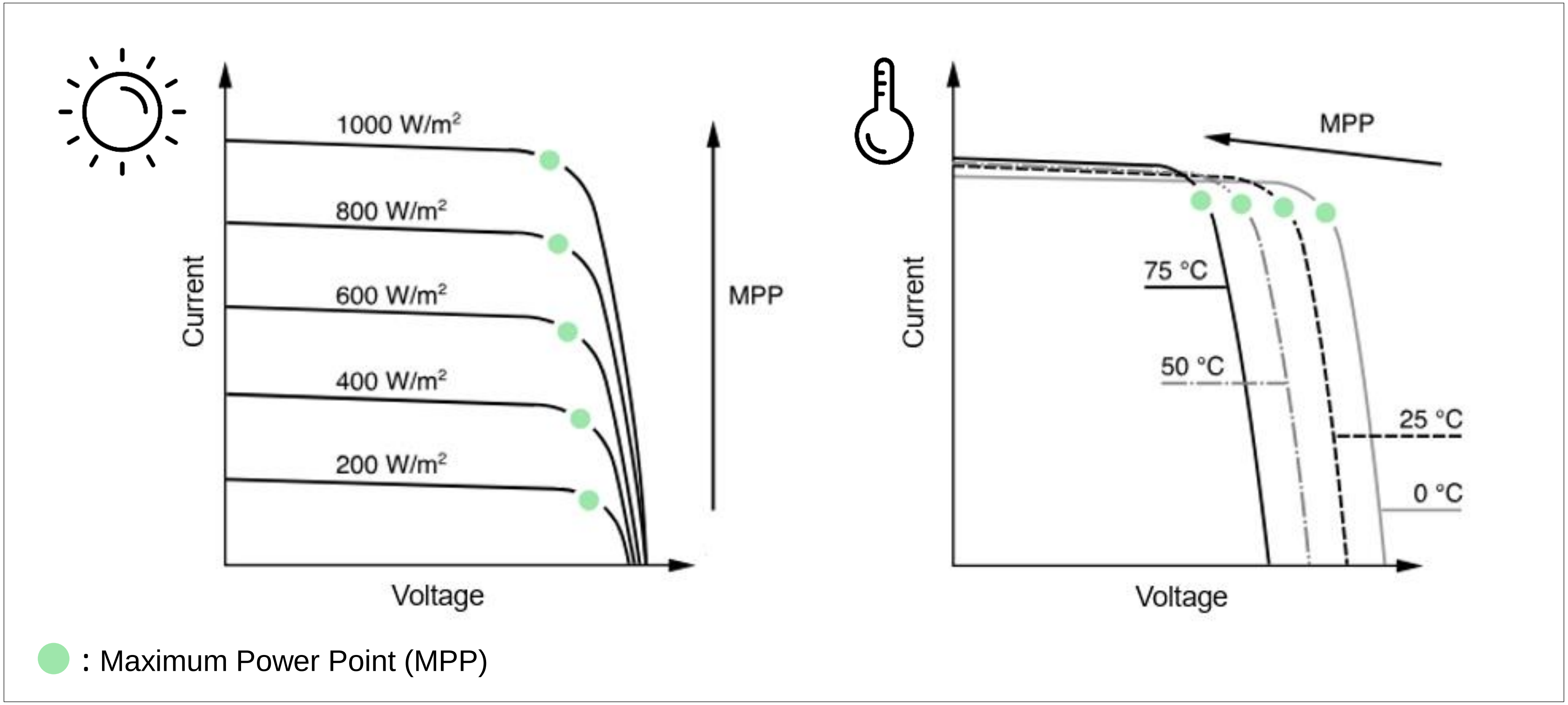


*Figure 4: Influence of irradiance and temperature on the photovoltaic effect.*

## Solar photovoltaic – The definition of the panel's efficiency

Solar panel efficiency is the ratio between the amount of electrical energy produced by the panel and the amount of irradiance that falls on its surface.

In order to compare the performance of different panel technologies, Standard Test Conditions (STC) have been defined, corresponding to an irradiance of 1000 W/m² and an ambient temperature of 25°C. In 2024, the average single-junction panel (with one solar cells layer) efficiency is **over 22%**.

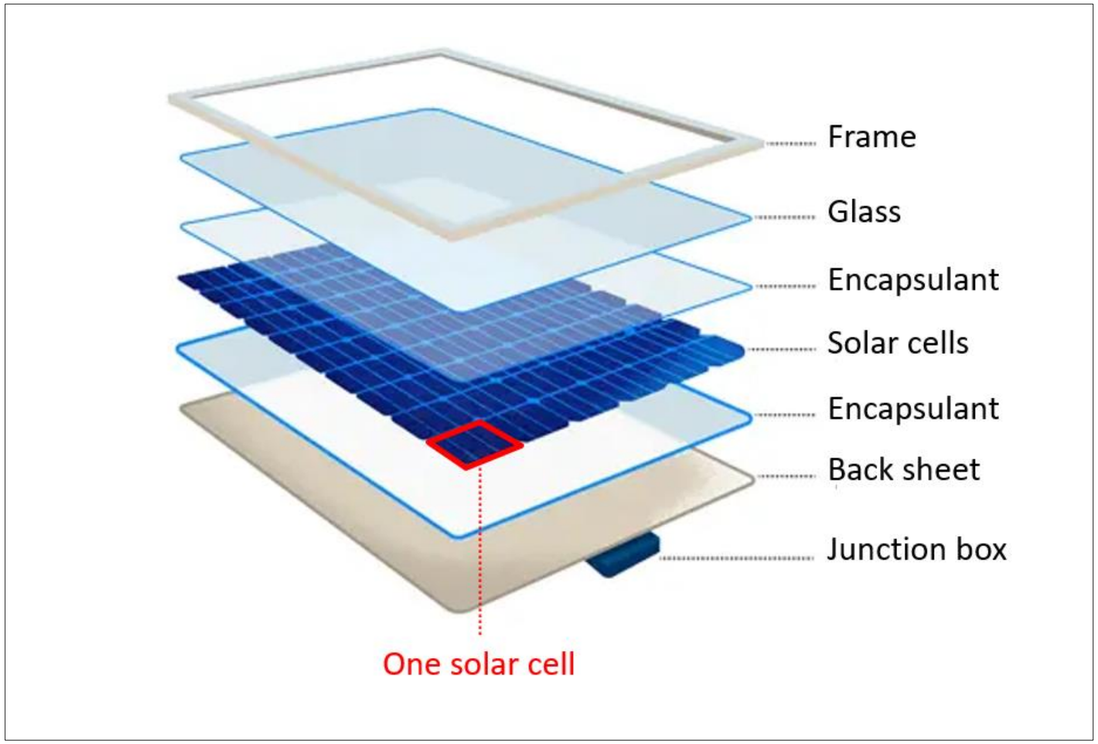


*Figure 5: Layers of a photovoltaic panel.*

# Solar photovoltaic – The physical limit of solar panel efficiency

Whatever the technological advancements, the efficiency of a single-junction panel (one solar cells layer) will not be able to exceed a certain limit of **33%.**

It is known as the Shockley-Queisser limit that arises from a property of standard photovoltaic materials called **the band-gap**, which determines the specific energy of photons that the material can most efficiently convert. Sunlight consists of photons with various energies; those below the band-gap are not used at all, while those above the band-gap may be captured, but any excess energy beyond the band-gap is lost.

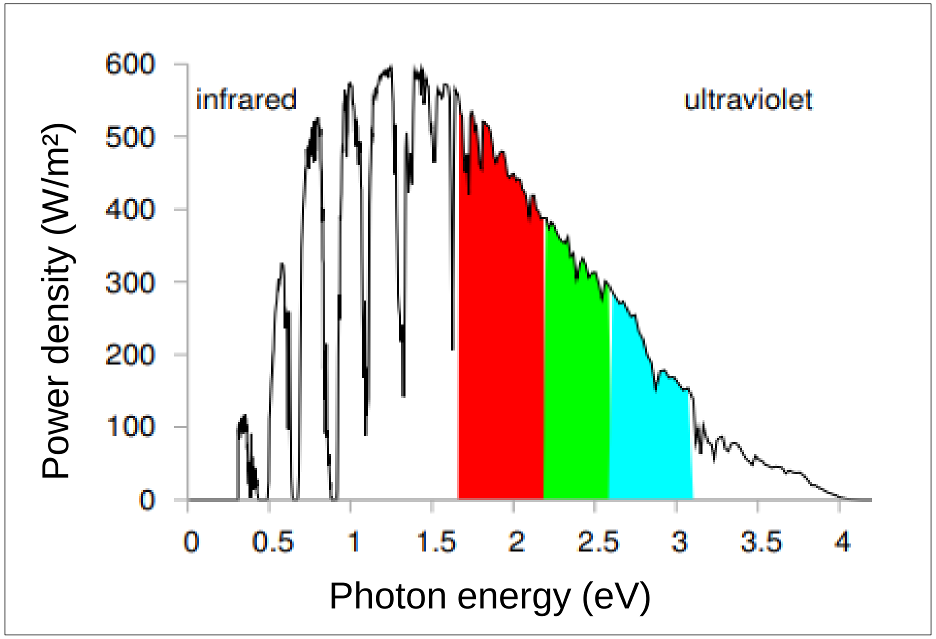


*Figure 6: The spectrum of midday sunlight.*

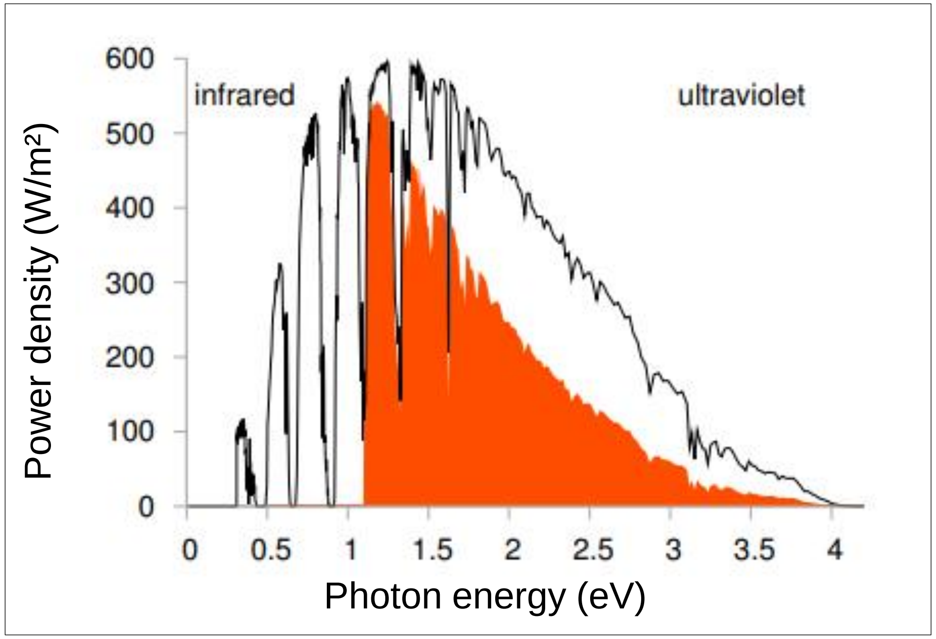


*Figure 7: Energy captured by a solar panel with a single band-gap at 1.1 eV (red area).*

# Solar photovoltaic – Solar cells: sunlight to electricity

A photovoltaic cell, made of semiconductor material, absorbs sunlight. This causes electrons to be dislodged, creating an electrical charge. Conductors in the cell collect these electrons. When connected to a load like a battery, the flow of electrons generates electricity in the circuit.

The majority of solar panels are constructed using polycrystalline silicon solar cells. These cells are made up of layers of silicon, phosphorus (N-type dopant) and boron (P-type dopant).

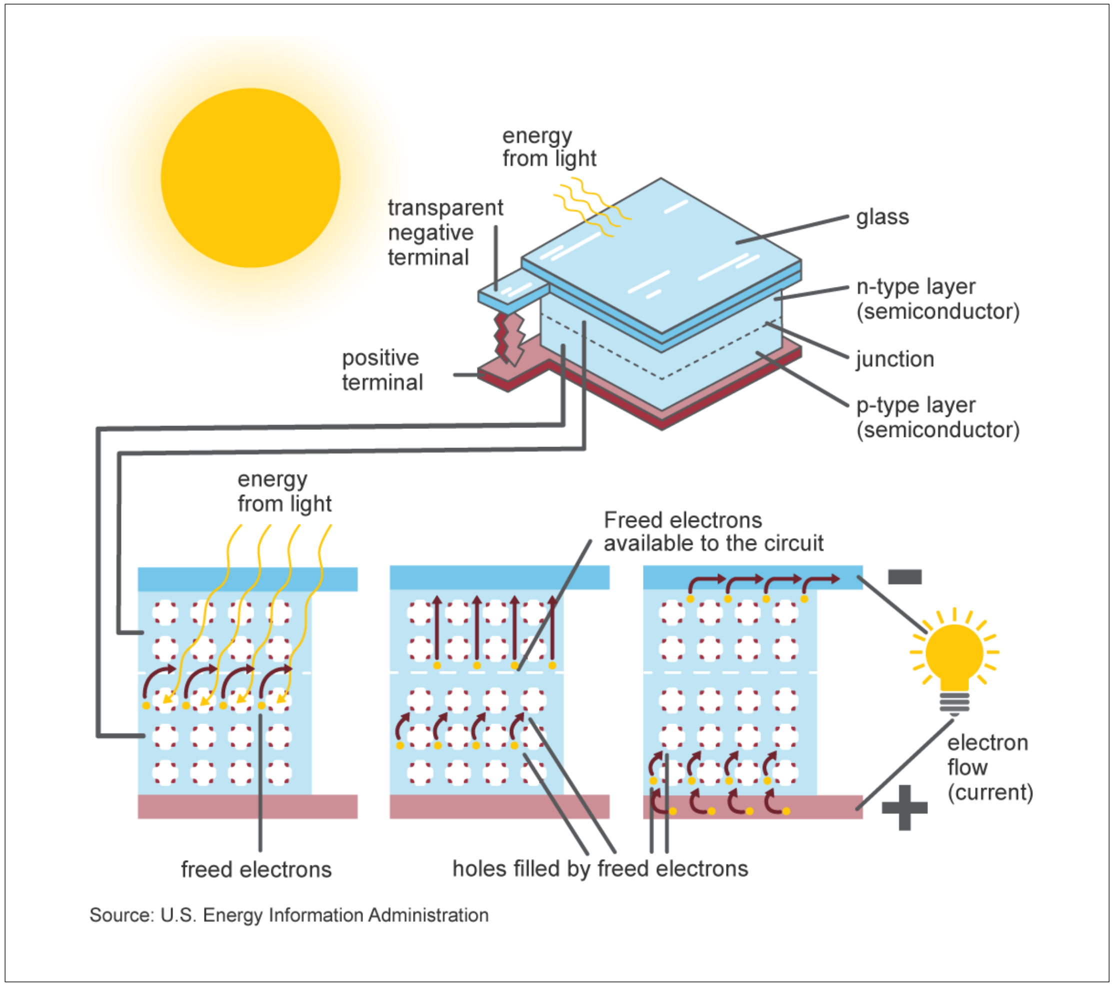


*Figure 8: Inside a solar cell.*

# Solar photovoltaic – Perovskite cells

A new type of cell, with the general formula $ABX_3$ in a perovskite structure, are a promising alternative due to their low production cost and high efficiency resulting in panels reaching 25% efficiency.
A is a cation, typically methylammonium $CH_3NH_3^+$, B is a lead cation $Pb_2^+$, and X is a halide anion iodide $I^-$.

However, perovskites face challenges such as instability and low resistance to external factors like water and temperature. Ongoing research aims to address these issues.

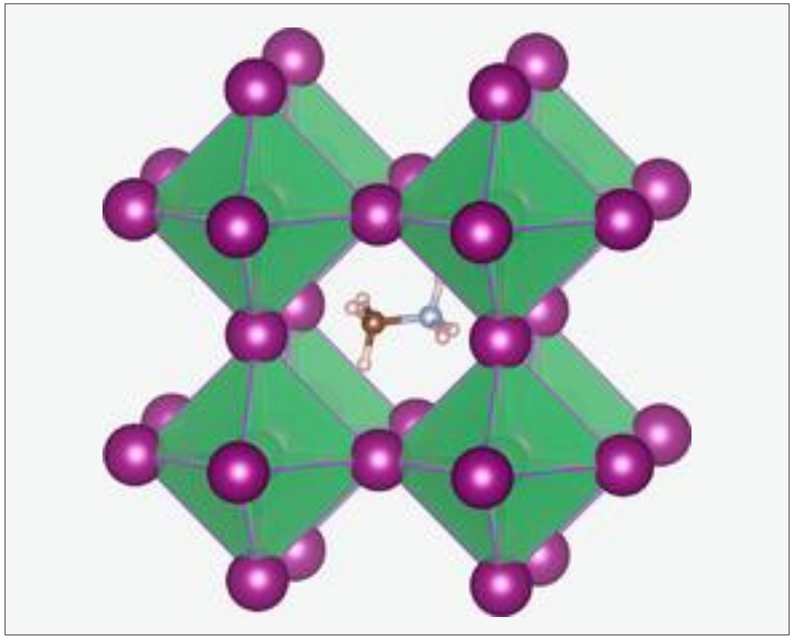

*Figure 9: Perovskite structure of $CH_3NH_3PbI_3$.*
*The cation $CH_3NH_3^+$ is surrounded by 8 $PbX_6$ octahedra.*

# Solar photovoltaic – Multi-junction cells

A superposition of cells with different properties, using different energy bands allowing for a broader spectrum of radiation capture. This type of cell is already on the market, mainly for space applications.

The efficiencies achieved are very promising (beyond 40% under concentrated sunlight).

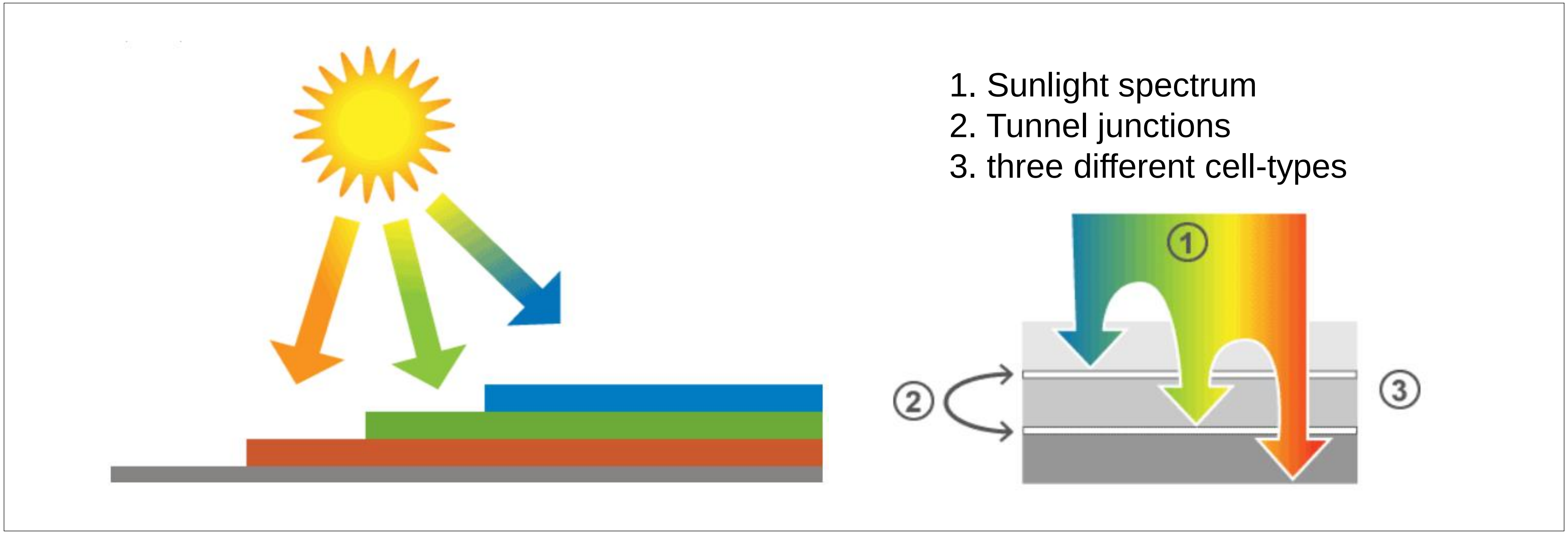


*Figure 10: Structure of a triple-junction cell.*

# Solar photovoltaic – The factors that influence efficiency

The panels operating efficiency **in real-world use** is determined by many factors:

- The photovoltaic cell efficiency, based on the solar cell design;
- The total panel efficiency, based on the cell layout and panel size;
- The solar irradiance and the temperature;
- Losses related to the environment, such as shading, dust, and dirt;
- The configuration of the installation, such as deviation from South and tilt.

| Deviation from South (°) \ Tilt angle (°) | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 68 | 85 | 94 | 99 | 100 | 99 | 94 | 87 | 77 | 64 |
| 10 | 68 | 85 | 94 | 98 | 100 | 98 | 94 | 86 | 76 | 64 |
| 20 | 68 | 85 | 93 | 96 | 98 | 97 | 92 | 85 | 75 | 63 |
| 30 | 68 | 84 | 92 | 95 | 96 | 94 | 90 | 83 | 73 | 62 |
| 40 | 68 | 83 | 90 | 92 | 93 | 91 | 87 | 80 | 70 | 59 |
| 50 | 68 | 82 | 87 | 89 | 89 | 86 | 82 | 75 | 66 | 56 |
| 60 | 68 | 81 | 85 | 86 | 85 | 82 | 77 | 70 | 62 | 52 |
| 70 | 68 | 79 | 82 | 82 | 79 | 76 | 71 | 65 | 57 | 49 |
| 80 | 68 | 77 | 79 | 77 | 75 | 71 | 66 | 60 | 53 | 44 |
| 90 | 68 | 75 | 75 | 73 | 69 | 65 | 60 | 53 | 46 | 39 |

*Figure 11: Decrease in the efficiency (%) of a PV system in Belgium respect to the optimal configuration.*

# Solar photovoltaic – The estimate production in Belgium

**<u>Domestic rooftop solar production:</u>**

**Assumptions:**

Every person has 8 m² of 22%-efficient solar panels installed to cover all south-facing roofs with a tilt of 40°.

$$22\% \times 117 \text{ W/m}^2 \times 8 \text{ m}^2 = 206 \text{ W} \Rightarrow \frac{206 \text{ W} \times 24\text{h}}{1{,}000} \approx \mathbf{5\ kWh/pers/d}$$

**<u>Solar farming production:</u>** (deployment of PV panels all over the coutryside)

**Data/Assumptions:**

(i) The land area per person equals to 2,623 m²/pers in Belgium and the average power per flat ground area is 117 W/m²;
(ii) The solar farms are equipped with 22%-efficient PV panels;
(iii) Let us assume that 0.5% of the country could be covered by solar farms.

$$22\% \times 117 \text{ W/m}^2 \times 2{,}623 \text{ m}^2\text{/pers} \times 0.5\% \approx 338 \text{ W/pers} \approx \mathbf{8\ kWh/pers/d}$$

# Solar photovoltaic – The installed capacity in Belgium

According to Elia, the total installed capacity of photovoltaic installations in Belgium in 2023 was 8.3 GW. In that same year, it produced 7.2 TWh of electricity (equivalent to 9.5% of the country's total electricity production).

This corresponds to $\frac{7.2 \times 10^9 \text{ kWh}}{11{,}700{,}000 \text{ pers}}$ **≈ 615 kwh/pers/y, which is 1.7 kWh/pers/d**

and a capacity factor of $\frac{7{,}200 \text{ GWh}}{8.3 \text{ GW} \times 24 \text{ h} \times 365}$ **≈ 10%**.

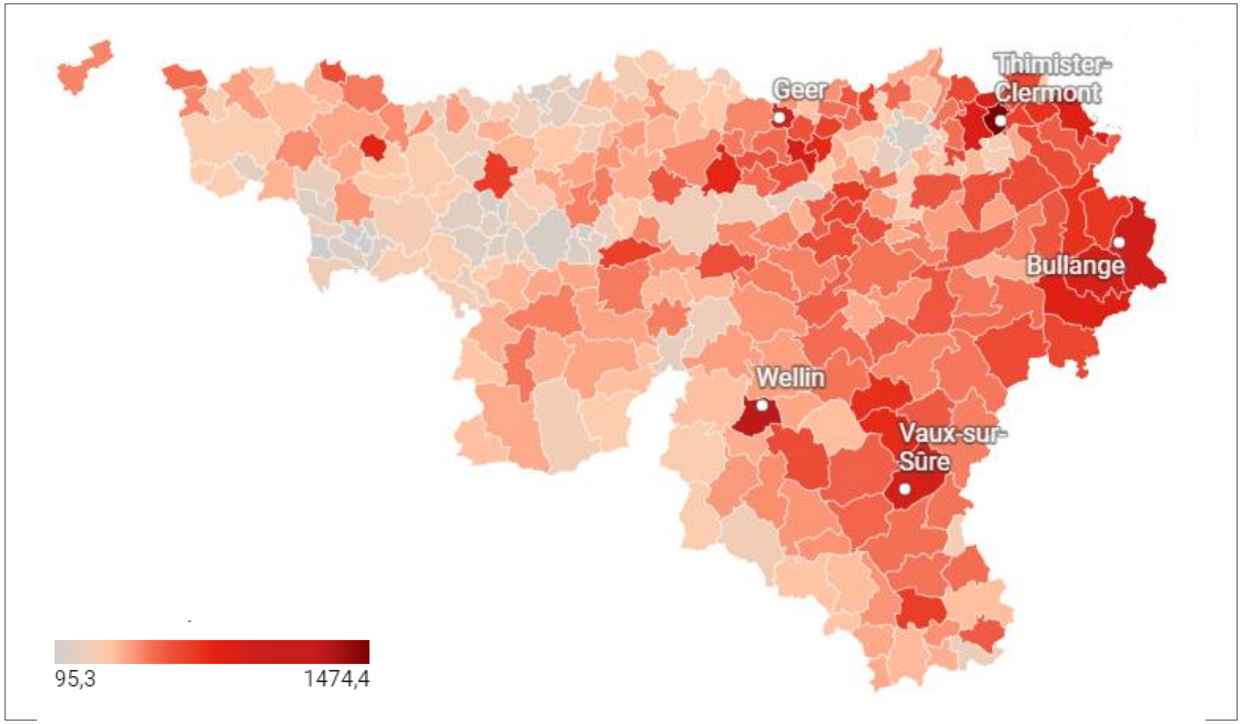


*Figure 12: Solar production in 2021 per municipality in Wallonia (in kWh/pers). The province of Liège had the highest number of households powered by solar energy (123,491).*

# Solar photovoltaic – The largest solar farm in Belgium

Kristal Solar PV Park located in Limburg is the largest solar farm in Belgium. It is a **99.5 MWc** solar PV power project spread over an area of 93 hectares (303,000 panels). The project was developed by ENGIE Fabricom and is currently owned by Limburgse Reconversie Maatschappij ; it generates 85,000 MWh of electricity per year.

What is capacity factor and the efficiency of this PV farm if assuming 110 W/m$^2$ of average solar irradiance? Be mindful of the assumptions made.

*Figure 13: Kristal Solar PV Park – Limburg, Belgium*

## Exercice 1:

We are in 2030. The price of photovoltaic energy has become very low. The EU-28 decides to heavily invest in this technology in southern Europe where solar resources are the best, in order to cover all its electricity consumption with PV. This consumption is assumed to be about 5,000 TWh.

**1.** What is the land area that these photovoltaic farms will need to occupy, knowing that (i) the efficiency of a photovoltaic panel is 25% and (ii) the sunlight in southern Europe is around 220 W/m²?

**2.** What would be the total cost of these farms in billion euros considering that (i) the price of PV per installed watt is 0.4 euro and (ii) the capacity factor of PV in southern Europe is around 30%?

# Solution:

**Part 1:**

A PV farm of 1 km² will produce $220 \times 8{,}760 \times 25\% \times 10^6$ = 0.4818 TWh over a year.

So, we will need an area equal to $\frac{5{,}000}{0.4818}$ **= 10,377 km²**.

**Part 2:**

5,000 TWh is the energy produced annually by a source with a constant power of $\frac{5{,}000}{8{,}760}$ = 0.57 TW.

Since the capacity factor of PV is 30%, we will need to install $\frac{0.57}{0.3}$ =1.9 TW of PV.

This will have a cost of $\frac{1.9 \times 10^{12} \times 0.4}{10^9}$ = **760 billion euros**.

# Solar photovoltaic – The rise of agrivoltaics

Agrivoltaics is a system that combines photovoltaic electricity production with agricultural production below the same surface. The synergy between both can translate into efficient land use, improved crop productivity due to shade regulation and reduced water stress, and enhanced solar panel efficiency through the cooling effect from plants' transpiration.

The first agrivoltaic project in Belgium has been in production since summer 2023. It covers an agricultural land of 13 hectares with an installed capacity of 10 MW.

*Figure 14: Chiba Ecological Energy – Japan.*

*Figure 15: EtherEnergy agri-PV project – Namur.*

# Solar thermal – The operation of a thermal panel

The solar energy is collected via a solar collector that is (usually) placed on the roof. In a flat plate collector, sunlight falls on a metal plate that is covered with a special layer which absorbs radiation. Behind this plate, a liquid flows in a tube, which absorbs the heat and transports it to the boiler tank.

The storage tank ensures that the solar heat can be stored and used later.

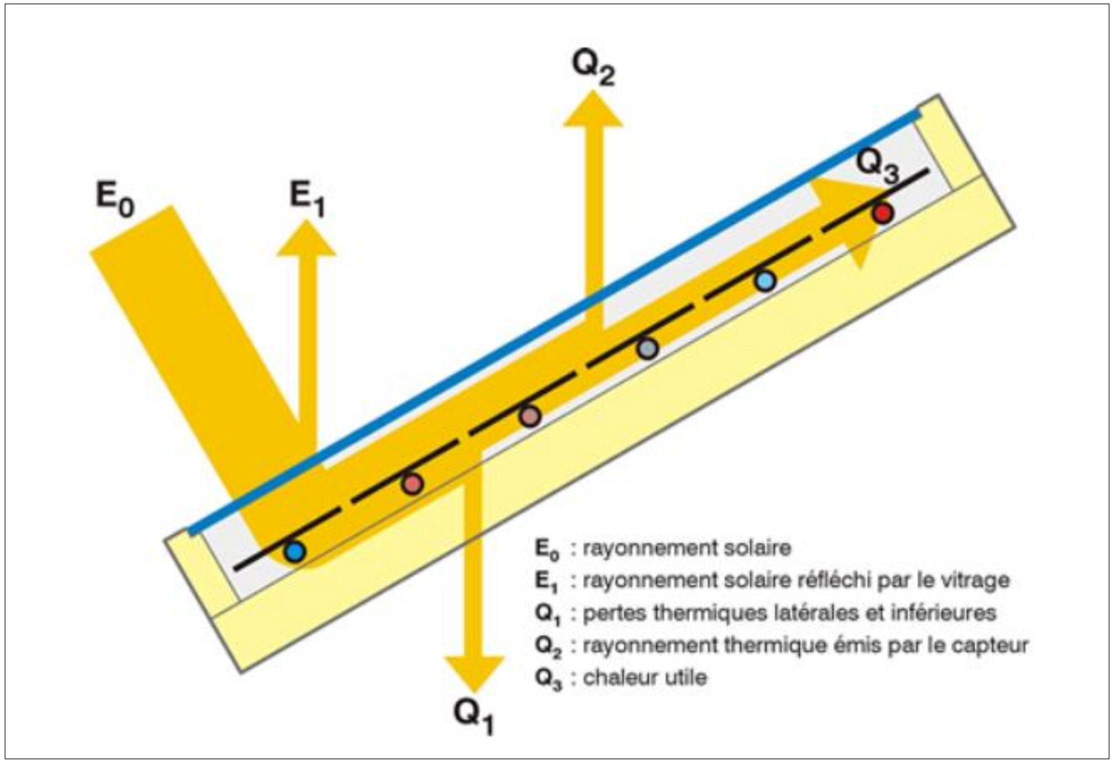


*Figure 16: The efficiency of a solar collector is the ratio between the useful heat (Q3) transmitted to the fluid and the incident solar radiation (E0).*

# Solar thermal – The production in Belgium

The efficiency of the thermal solar installation obviously does not depend solely on the efficiency of the collectors. Thermal losses will occur during the storage of hot water, during the transfer of heat transfer fluids between the collectors and the solar tank, and between the tank and the various points of use.

**Data/Assumptions:**

(i) Various dynamic simulations have shown that the average efficiency of a well-designed installation is around 30 - 40%;
(ii) Every person has 8 $m^2$ of 35%-efficient solar thermal panels;
(iii) The panels are installed to cover all south-facing roofs with a tilt of 40°.

With irradiation levels in Belgium around 1,000 kWh/$m^2$/year, they will capture:

$$35\% \times \frac{1{,}000}{365}\,\text{kWh/m}^2\text{/d} \times 8\ \text{m}^2 = \mathbf{7.5\ kWh/pers/d}$$

**Comment:** In practice we would have to choose whether to use the 8 $m^2$ of roofs for thermal or photovoltaic panels. Here we will just choose to add up these two numbers to the production stack.

# Solar biomass – Processes

The four main routes for obtaining energy from solar-powered biological systems:

**1.** Growing specifically chosen plants and burning them to produce electricity or heat, known as coal substitution.

**2.** Cultivating plants like sugar cane or corn and converting them into ethanol or biodiesel for use in vehicles or aircraft, or cultivating genetically-engineered bacteria, cyanobacteria, or algae that directly produce hydrogen, ethanol, or butanol. This is referred to as petroleum substitution.

**3.** Using by-products from other agricultural activities to create biofuels.

**4.** Growing plants to be directly consumed by energy-requiring humans.

# Solar biomass – The production in Belgium

For all these processes, the initial point where energy is harnessed is a chemical molecule (or several), such as a carbohydrate. We can estimate the maximum power obtained from any of these processes by considering how much power could pass through this primary stage.
Subsequent steps, involving tractors, animals, chemical facilities (**for producing among others fertilizers!**), and power stations, are prone to energy loss.

What is the amount of solar biomass energy we can produce?

**Data/Assumptions:**

(i) The harvestable power of sunlight in Belgium is 117 W/m²;

(ii) Most efficient plants in Europe are about 0.5%-efficient at specific light levels in turning solar energy into chemical energy;

(iii) We devote 50% of the country for bionenergy (1,312 m² of land per person);

(iv) Assume that only 35% losses occur along the processing chain.

$$0.5\% \times 117\ \text{W/m}^2 \times 1{,}312\ \text{m}^2\text{/pers} \times 65\% = 0.5\ \text{kW/pers} \approx \mathbf{12\ kWh/pers/d}$$

# Solar biomass – Power density for different plants

In tropical plantations, genetically modified plants can deliver up to 1.5 $W/m^2$ with fertilizer application and irrigation.

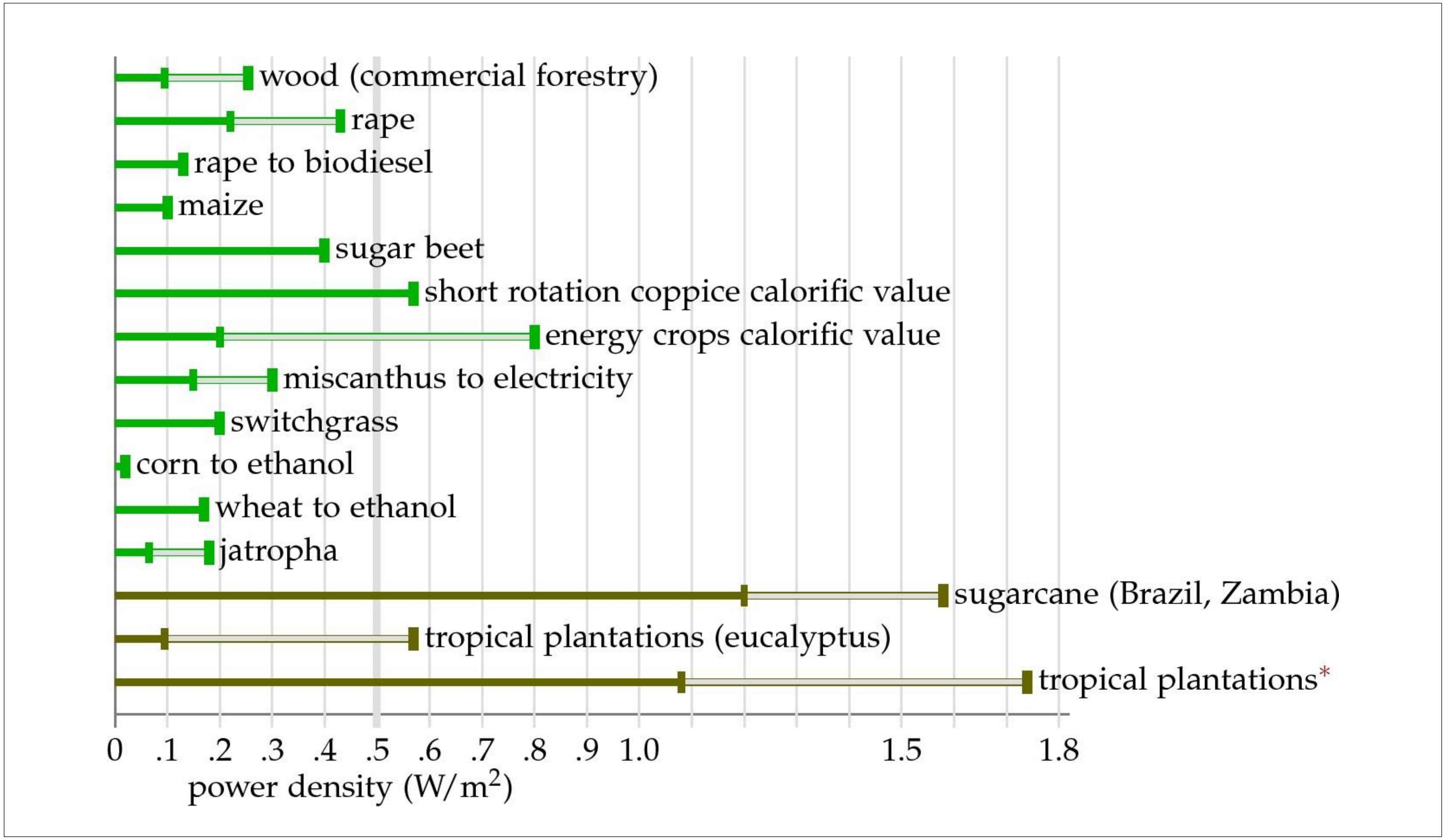


*Figure 17: Power production, per unit area, achieved by various plants.*

# Completion of the current balance sheet

## Balance sheet

**CONSUMPTION**

- Plane: **5 kWh/pers/d**
- Car: **30 kWh/pers/d**

**PRODUCTION**

- Solar (biomass): **12 kWh/pers/d**
- Solar (thermal): **7.5 kWh/pers/d**
- Solar farming: **8 kWh/pers/d**
- Solar (PV): **5 kWh/pers/d**
- Wind: **8.75 kWh/pers/d**

# <u>Exercice 2:</u>

The government wants to cover all the electricity needs of Belgium by burning wood. A power plant burning wood has an efficiency of 40%. Compute the amount of land that should be dedicated to growing forests to provide enough wood for the electric plants (in a sustainable way).

Data: (i) The Belgian electricity consumption is 78.4 TWh and (ii) a forest in Belgium transforms solar energy into chemical energy at a rate of 0.2 $W/m^2$.

## Solution:

Over a year, each square meter of forest produces 0.0002 kW × 8760 h = 1.752 kWh of chemical energy.

Knowing that the conversion efficiency to electricity is 40%, only 1.752 kWh × 0.4 ≈ 0.7 kWh of electrical energy is produced per year with one square meter of forest.

It would therefore take $\frac{78.4\times10^9}{0.7} = 112\times10^9$ = **112,000 km²** of amount of land to be devoted for growing forest.

This corresponds to 3.6 times more of the Belgian territory.

# Solar biomass – What about algae?

Algae are plants that are not more efficient at photosynthesis than their terrestrial cousins. However, in water they can produce up to **4 W/m²** with enriched carbon dioxide by requiring 60 g of $CO_2$ per $m^2$ per day.

If all the $CO_2$ from all Begium power stations was captured (roughly 1.8 tons per person per year), it could service 82 square meters per person of algae-ponds (3% of the country's surface area).

This would produce $\frac{4 \text{ W/m}^2 \times 24 \text{ h}}{1{,}000} \times 82 \text{ m}^2\text{/pers}$ **≈ 8 kWh/pers/d**

*Figure 18: Qualitas Health algae cultivation site in Imperial, Texas.*

# Solar biomass – And about algae that produces hydrogen?

Hydrogen can be produced directly from the photosynthetic system, right from step one while carbohydrates require many chemical steps. This could be potentially a much more efficient way for producing energy.

Research studies have suggested that genetically modified algae covering 11 hectares in the Arizona desert could produce 300 kg of $H_2$ per day. Hydrogen contains 39 kWh per kg ⇒ algae-to-hydrogen facility would deliver 4.4 W/m².

*Figure 19: Horizontal and stacked tubular algae reactors consisting of several connected loops (Algae PARC Wageningen University).*

# Exercice 3:

Green kerosene, synthesized from algae grown in $CO_2$-enriched water, is currently considered by some energy sector actors as a credible alternative to fossil-based kerosene. It has the merit of being $CO_2$ neutral. Such an algae cultivation system is able to convert solar energy into chemical energy contained in the algae to produce kerosene.

**1.** We consider the supply of green kerosene for a Brussels - New York flight with a Boeing 747. Calculate how many liters of kerosene (10.3 kWh/l) will be burned by this plane during a Brussels - New York trip of 7,838 km. It will be considered that the plane’s fuel consumption during this trip is equal to the consumption it would have if it covered the entire distance at cruising speed.

Data: (i) At cruising speed, a Boeing 747 flies at 936 km/h and (ii) has a thrust of approximately 120 kN. (iii) The efficiency of its engines is 33%.

**2.** Calculate the surface area of algae cultivation necessary to supply green kerosene for a Brussels - New York flight per year with a Boeing 747.

Data: The conversion of solar energy into chemical energy contained in the algae is at an average rate of approximately 4 W/m² of culture. Half of this energy is lost during the production of green kerosene.

# Solution:

**Part 1:**

The chemical energy burned by the engines is $\frac{1}{0.33} \times 120{,}000\ \text{N} \times 7{,}838{,}000\ \text{m} \approx 2{,}850 \times 10^9$ J.

This corresponds to $\frac{2{,}850 \times 10^9}{3.6 \times 10^6} \approx 791{,}667$ kWh which is equivalent to 791,667 / 10.3 ≈ **76,860 liters of kerosene**.

**Part 2:**

Over a year, each square meter of algea produces 4 W × 8760 h = 35,040 Wh of chemical energy. Half of this energy is lost during the production of green kerosene, so each square meter of algea produces 17,520 Wh of green kerosene.

It means that $\frac{791{,}667}{17.52} \approx$ **45,186 m²** (4.5 hectares) of algea cultivation could allow the production of green kerosene for a Brussels - New York flight per year with a Boeing 747.

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